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JOHN W. FINCH, DIRECTOR

INFORMATION CIRCULAR

INDUCTION PROSPECTING FOR SHALLOW ORE DEPOSITS AND SMALL METALLIC OBJECTS

BY

J. W. JOYCE

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INDUCTION PROSPECTING FOR SHALLOW ORE DEPOSITS AND SMALL METALLIC OBJECTS[1]

By J. W. Joyce[2]

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INTRODUCTION

The geophysical section of the United States Bureau of Mines has received many inquiries regarding the application of geophysical methods to the location of small, buried metallic objects.

The object of this paper is fourfold: (1) To sketch as briefly and non-technically as possible the principles underlying the operation of several electrical geophysical methods of prospecting applicable to the finding of small, buried metallic objects; (2) to point out the possibilities and limitations of these methods; (3) to present, whenever possible, data showing actual results obtained from their use; and (4) to enumerate and describe methods that lack scientific background or foundation.

Elementary Principles

In discussing the principles underlying the operation of some of the electrical methods of geophysical prospecting certain technical terms, such as "magnetic field", "induced voltage", "reactance", and "resonance", inevitably must be used. For the benefit of the reader unfamiliar with their meaning a brief exposition of these terms is presented.

Magnetic field. - Everyone is familiar with the ordinary bar magnet and its ability to attract pieces of iron or steel. If such a magnet is placed under a sheet of paper covered with a thin layer of fine iron filings and the paper is jarred slightly the filings will aline themselves in a pattern similar to that shown in figure 1. This simple experiment demonstrates the existence of a magnetic field of force about the magnet. This field is composed of numerous lines of force, indicated by the lines of iron filings.

The region over which the lines of force enter the magnet is called the south pole and the opposite end, where the lines of force leave the magnet, the north pole. Every magnet always has a north and a south pole.

At every point about the magnet the magnetic field has a definite direction-the direction of the lines of force - and a definite strength or intensity; the nearer the point to one of the poles the greater the intensity. (See fig. 1.) This can be shown experimentally by moving a piece of iron toward one end of a horseshoe or bar magnet; the nearer the piece to the end the stronger the force of attraction acting on it.

The intensity and direction at any point in a magnetic field may be represented by a straight line that points in the direction of the field and is proportional in length to the strength of the field, as shown at points A, B, and C, figure 1.

In addition to permanent magnets there are electro-magnets. One of the fundamental discoveries of electricity was the fact that whenever a current flowed in an electric conductor a magnetic field surrounded the conductor, as shown in figure 2,A. Furthermore, the strength of the magnetic field in air was found to be directly proportional to the current in the wire. Thus, if the current was doubled the strength of the magnetic field also doubled.

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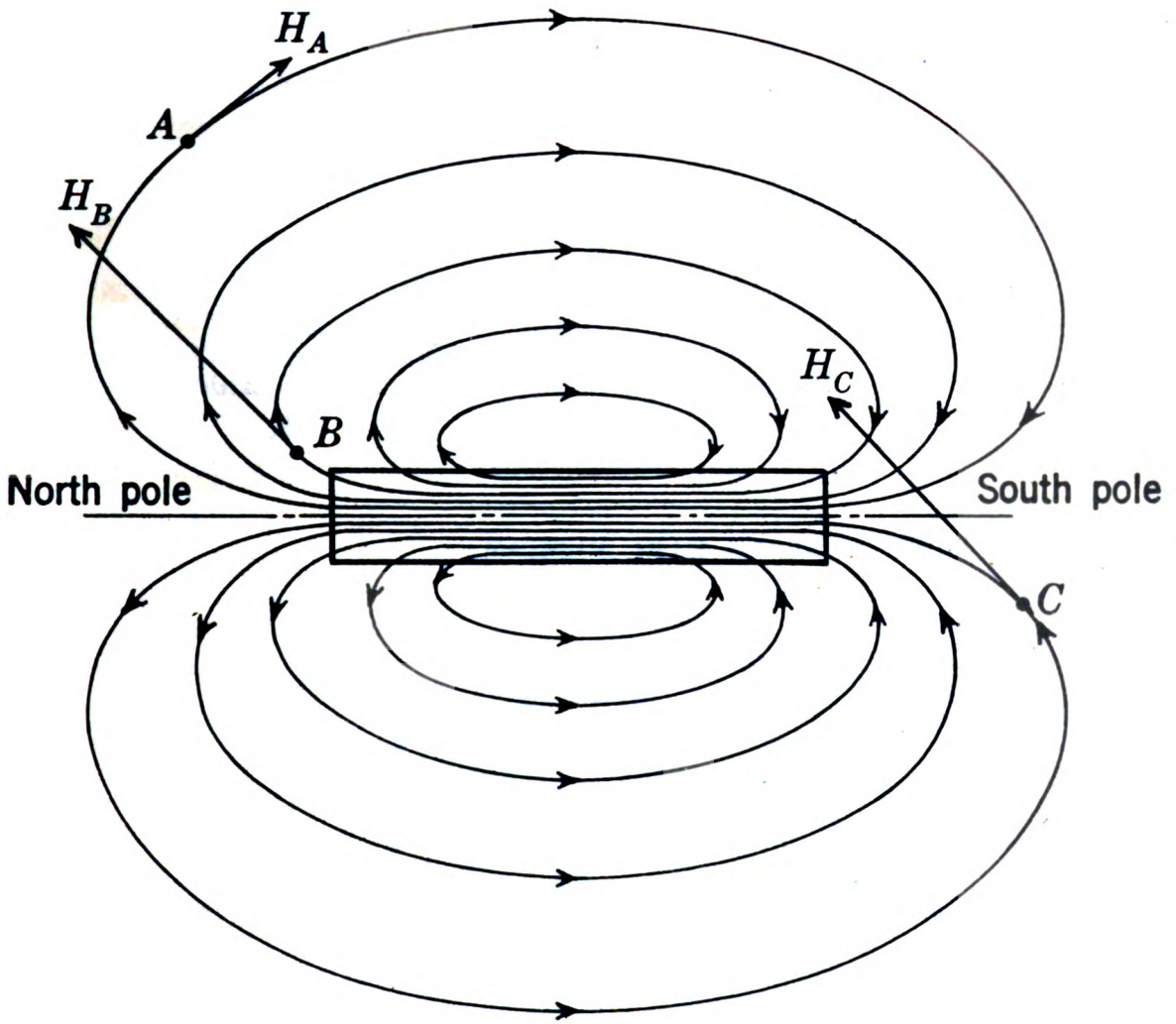

Figure 1.— Magnetic field of bar magnet.

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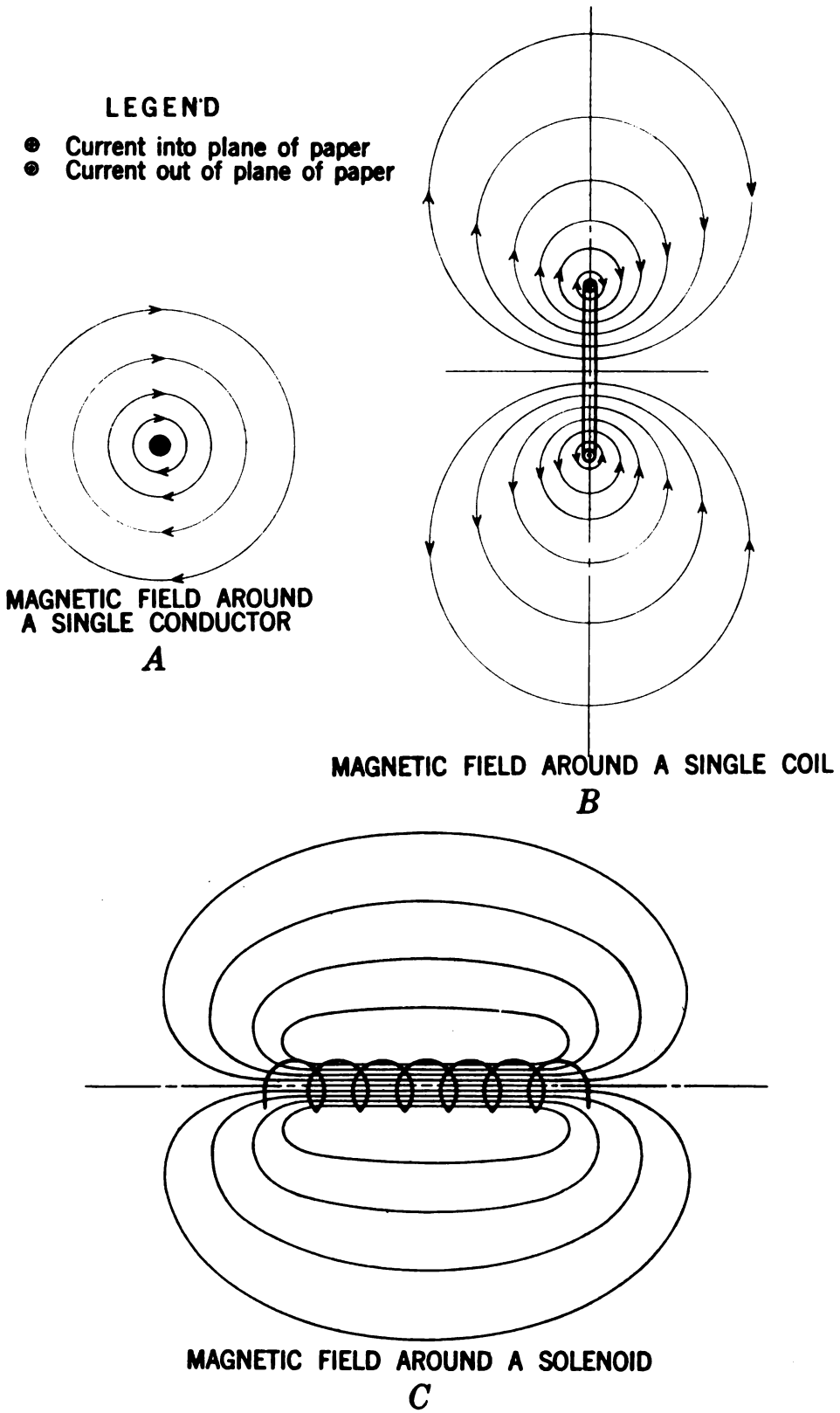

Figure 2.— Electromagnetic fields: *A*, Magnetic field around a single conductor; *B*, magnetic field around a single coil; *C*, magnetic field around a selenoid.

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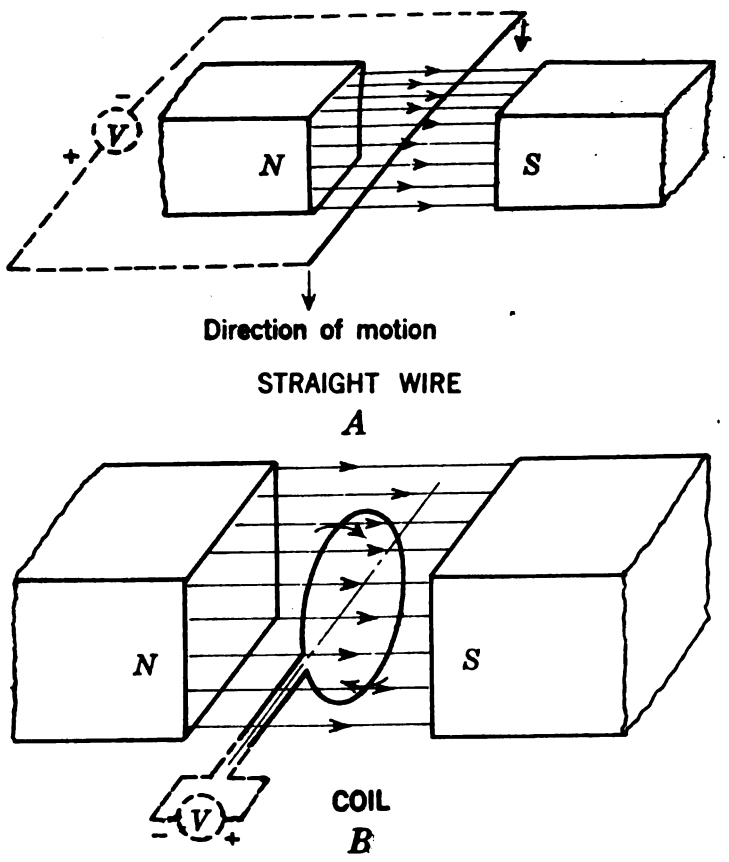

Figure 3.— Electromagnetic induction: *A*, Straight wire; *B*, coil.

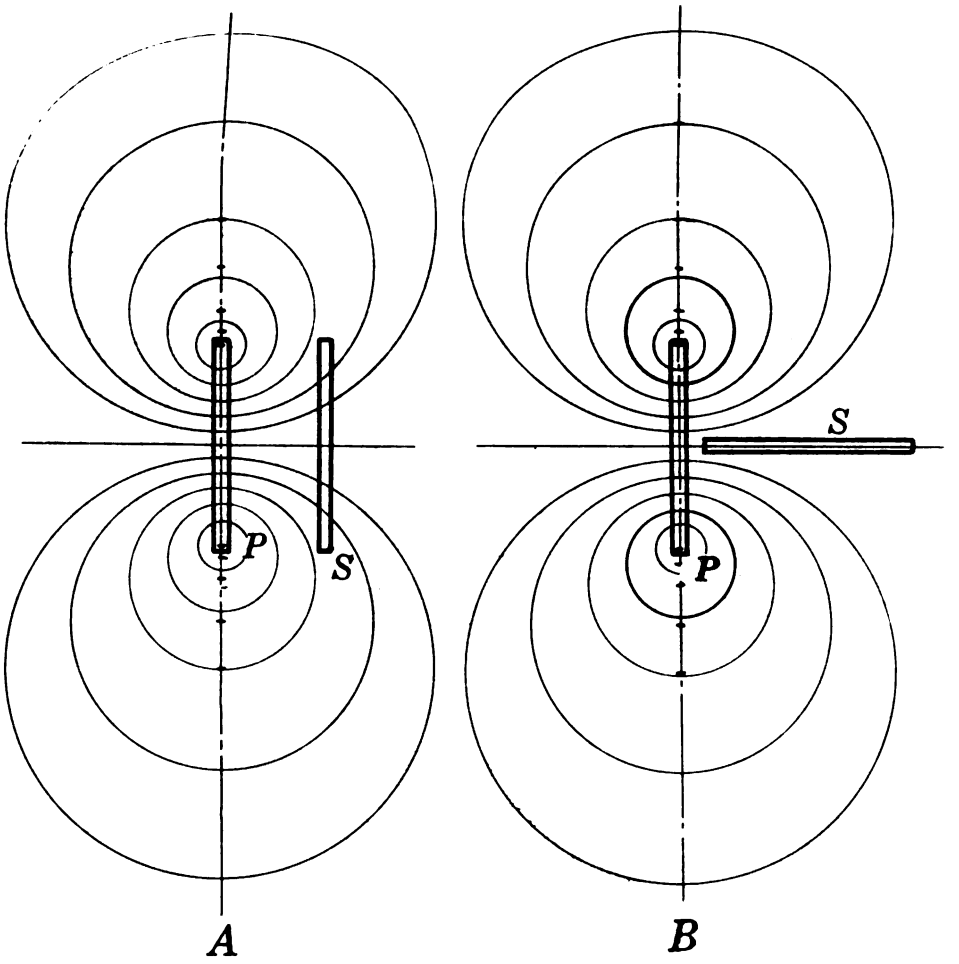

Figure 4.— Mutual inductance.

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If a single turn of wire is wrapped around a wooden form and a current is passed through the wire a magnetic field will surround the loop (fig. 2,B). If this same current is now passed through 5 turns of wire instead of 1 turn the resulting magnetic field will be 5 times as strong, because each turn is producing a magnetic field which adds to the field of every other turn. Thus, if a current of I amperes is passed through a coil of N turns of wire (fig. 2,C), the resulting magnetic-field strength will depend on the product NI. This product is referred to as the "ampere-turns" of the coil.

When a coil is connected to a source of constant voltage a direct current flows, and the resulting magnetic field is steady. If an alternating voltage is used the current, and hence the magnetic field, will also alternate from positive to negative values; that is, at one time the magnetic field will be in one direction, and an instant later it will have changed to the opposite direction. Thus, there are alternating as well as direct magnetic fields. In the methods to be described only alternating fields are used.

Induced voltage. - If an electrical conductor, such as a piece of wire or a metal bar, is moved through a steady magnetic field so that it cuts across the lines of force, as shown in figure 3,A, a voltage or potential difference will exist between the two ends of the conductor. The amount of this voltage will depend on the total rate at which the conductor cuts the lines of force. For example, suppose a conductor cuts lines of force at the rate of 100,000,000 a second; then the potential difference between the ends of the conductor will be 1 volt. If the rate of cutting is increased a hundred times the potential difference will now be 100 volts. The rate of cutting may be increased by increasing the length of the wire in the field, increasing the strength of the field, increasing the speed of cutting, or combinations of these methods.

As soon as the conductor ceases to cut magnetic lines of force the voltage across the ends becomes zero.

Suppose, instead of a straight conductor, a circular coil of wire of one turn, as shown in figure 3,B, is used. If this coil is rotated so that the number of lines of magnetic force through it changes a voltage will appear across the two ends of the coil. This voltage will depend on the rate at which the lines of force inside the loop increase or decrease. Thus, if the rate of change is 100,000,000 lines a second, 1 volt will be generated in the coil. Now, if instead of having only 1 turn of wire the coil had 10 turns then for the same rate of change of lines of magnetic force, 10 volts would be generated, since each turn adds to the voltage of every other turn.

Up to this point it has been assumed that the conductor moved and the magnetic field remained stationary. The same result would have been obtained if the conductor remained stationary and was cut by a moving magnetic field. The law of induction states that whenever a conductor cuts lines of magnetic force as a result of any relative motion between the conductor and the magnetic field a voltage will be generated in the conductor.

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Again, if a conductor is placed in an alternating magnetic field - that is, a magnetic field that is continually passing from the maximum value in one direction to the corresponding maximum in the opposite direction - an alternating voltage of the same period or frequency as the magnetic field will be generated in the conductor.

Self-inductance. - If a coil of wire is connected to a direct or steady voltage, as, for example, a battery, the resulting current will be determined by the resistance of the coil. If this same coil is now connected to an alternating voltage equal to the preceding direct voltage the alternating current in the coil will be less than the direct current. In other words, something besides resistance now impedes the flow of current. This quantity is the opposing voltage of self-inductance of the coil. It is due to the fact that the alternating current flowing in the coil produces an alternating magnetic field. This field cuts the turns of wire on the coil and generates an alternating voltage which always opposes the applied voltage.

E = applied alternating voltage,
I = resulting current through coil,
E_L = countervoltage of self-inductance coil,
X_L = inductive reactance of coil,
f = frequency of applied alternating voltage,
π = 3.1416.

Then $E_L = IX_L$ and $X_L = 2\pi fL$.

Factor L is known as the coefficient of self-inductance of the coil. For any one coil it is a constant, and its value depends on the shape, size, method of winding, and number of turns of the coil.

Mutual inductance. - Consider two coils placed as shown in figure 4,A. If an alternating current flows in coil P the resulting alternating magnetic field will cut coil S, and voltage will be generated in the latter. At any particular separation of the coils the maximum lines of force from P will cut S when P and S are parallel (fig. 4,A). If S is now turned until it is in the position shown in figure 4,B, none of the lines of force from P pass through S, and hence no voltage is generated in the latter.

Let X_M = voltage generated in S due to unit current in P,
f = frequency of current in P,
π = 3.1416,
$X_M = 2\pi fM$.

Here, M is known as the coefficient of mutual inductance between P and S. It depends on the shape, size, methods of winding, and turns on P and S and their positions relative to each other. For the case shown in figure 4,B, M is equal to zero.

Capacity. - An electric condenser consists of two metal plates separated by some insulating material, such as air, mica, paper, oil, or similar substances. When placed in series with a source of direct voltage, barring a small initial

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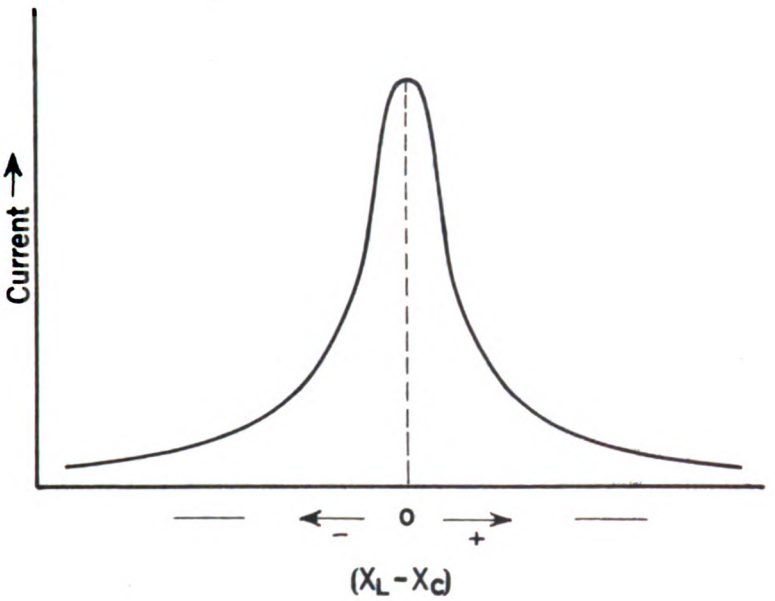

Figure 5.—Relation between current and reactance.

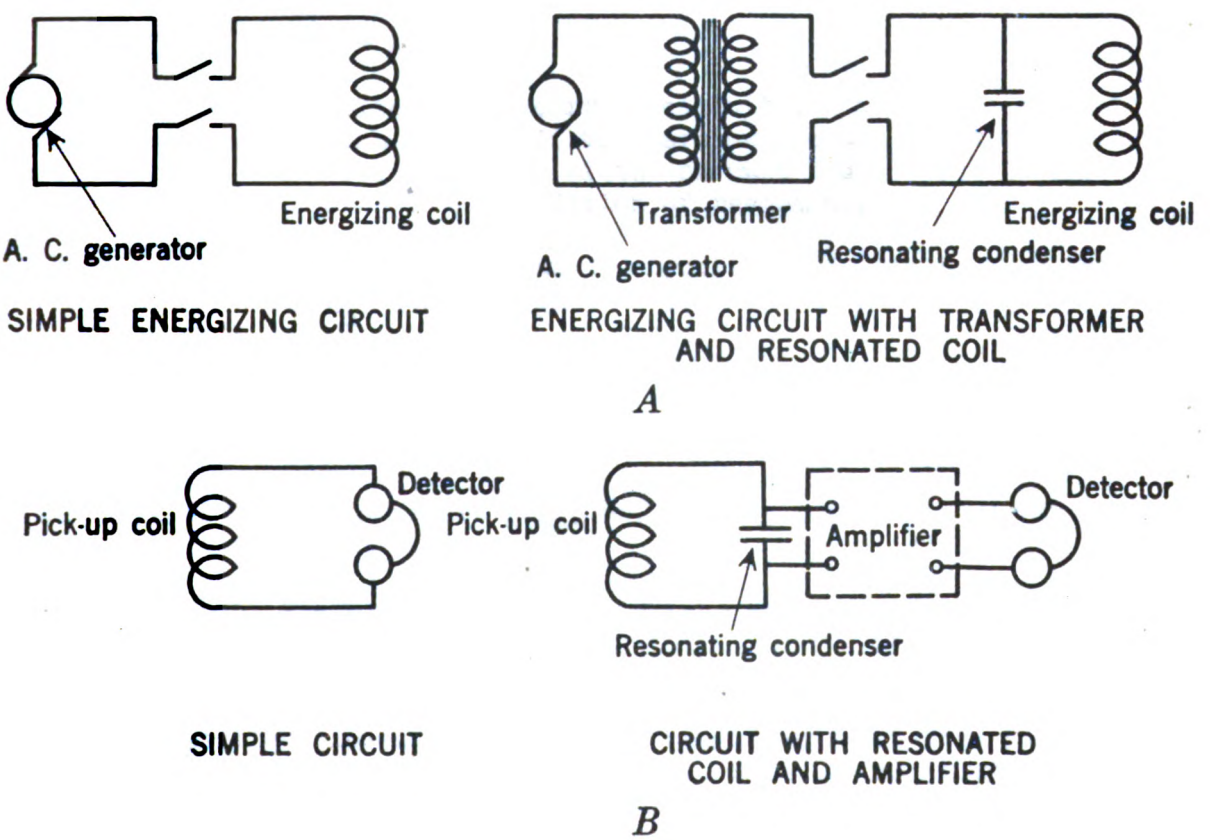

Figure 6.—*A*, Energizing circuits; *B*, pick-up circuits.

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transient, no appreciable current will flow; that is, the condenser completely blocks off any current. However, if an alternating current is used current will flow, the amount depending on the capacity of the condenser and the frequency of the applied voltage. The capacity is constant for a given condenser; it depends on the shape, size, and separation of the plates and the insulating material between them.

Let E = applied alternating voltage,
I = resulting current through condenser,
X_c = capacity reactance due to condenser,
C = capacity of condenser,
f = frequency of E, the applied voltage,
π = 3.1416.

Then $I = \frac{E}{X_c}$ and $X_c = \frac{1}{2\pi fC}$

Impedance. - When an alternating current flows through an electrical circuit containing resistance (R), inductive reactance (X_L), and capacitive reactance (X_c) the current is impeded by all three quantities. This combined effect is called the total impedance (Z) of the circuit, and its value is found to be

$$Z = \sqrt{R^2+(X_L - X_c)^2} \ .$$

Resonance. - In an alternating-current circuit the inductive and capacitive reactances act against each other. If they are made equal their combined effect becomes zero, and the total impedance of the circuit becomes equal to its resistance. This is known as the condition of resonance.

The relationship between inductance, capacity, and frequency at resonance can be found by making X_L equal to X_c. Thus,

$$X_L = X_c$$

$$2\pi fL = \frac{1}{2\pi fC} \ .$$

If any 2 of the 3 quantities L, C, and f are given the other may be found by solving the above equation.

Figure 5 shows the way in which the current varies as $X_L - X_c$ is varied.

Since at resonance the only factor limiting the current is resistance it follows that the current will be the maximum for a given voltage. A familiar example which utilizes resonance to produce maximum current flow for a given voltage is found in the tuning of a radio set. Here the value of the capacity is changed until the maximum volume is obtained.

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INDUCTION METHODS

General

Induction methods of geophysical prospecting usually embrace four cardinal features: (1) A source of electrical energy, (2) a primary or exciting loop, (3) one or more exploring or pick-up coils, and (4) a detecting device. Each of these factors, together with other points of interest, will be discussed in a general way before specific methods are described.

Source of electrical energy. - The source of electrical energy used depends on the frequency of alternating current desired. At frequencies below 1,000 cycles per second hand-driven or small gasoline-driven alternators sometimes are used, while above that value vacuum-tube oscillators meet the need. The latter usually receive their energy from generators or batteries. They simply change the direct or low-frequency alternating current of the generator or batteries to higher-frequency currents. Unless otherwise noted, most of the induction methods described in this report may be effectively operated at a frequency of 500 cycles per second.

Primary or exciting loop. - The electrical energy produced by the generator or oscillator is supplied to the primary or energizing loop, which translates the electrical energy into magnetic energy in the form of an alternating magnetic field of frequency equal to the frequency of the supplied electrical current.

The size and location of the primary loop depend on the particular method used, but in all cases it is so placed that the portion of the ground to be explored is subjected to the primary magnetic field.

Exploring or pick-up coils. - Exploring or pick-up coils are used to determine and map out the shape of the magnetic field over the ground being investigated. This is done by observing the induced voltages in the pick-up coil or coils when placed in various directions at different points on the ground.

Detecting device. - The purpose of the detecting device is to convert the voltage of the exploring coil into an audible sound or the visible deflection of a meter. At frequencies below 100 the alternating voltage of the exploring coil is rectified and indicated on a sensitive meter. From 100 to about 3,000 cycles per second ordinary radio headphones act as detectors, changing the voltage to an audible note. Above this range vacuum-tube voltmeters may be used in conjunction with an amplifier and a suitable meter.

Maximum effective range. - To realize the greatest possible effective range for any induction method two conditions must be met. First, the maximum number of ampere-turns in the primary loop for a given source of energy as well as the largest practical coil area must be obtained; second, effective amplification of the pick-up-coil voltage must be realized.

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To obtain the maximum number of ampere-turns in an energizing coil the impedance of the latter must be decreased enough to allow the maximum current available from the generator to flow in the coil. As has been pointed out, the impedance is made up of inductive reactance and resistance. Inductive reactance may be eliminated by resonating the coil with a condenser of proper size connected across its terminals. Resistance may be diminished by increasing the size of the wire, although practical considerations limit the use of excessive sizes. The same is true of the number of turns and the size of the coil.

If, when the coil is resonated, its impedance allows a current greater than the maximum allowable generator current to flow a step-down transformer may be used to reduce the voltage to the coil terminals.

As a numerical example of the foregoing statements consider a generator having a maximum energy output of 250 volt-amperes at 100 volts, giving a full-load current of 2.5 amperes. Assume a frequency of 500 cycles per second. Let 100 ohms represent the impedance of the energizing coil 10 ohms of resistance and 99.5 ohms of an inductive reactance. If a condenser having a capacity of 0.0000032 farad is connected across the coil the inductive reactance vanishes, and the total impedance is reduced to 10 ohms; but if the 100-volt generator supply is connected directly across the energizing loop 10 amperes will flow, whereas the full-load generator current is only 2.5 amperes. However, if a step-down transformer having a ratio of 2 to 1 is used the secondary voltage will be 50 volts, giving a coil current of 5 amperes or 250 watts input to the coil; if the transformer losses are neglected this just equals the generator full-load output. Thus, without resonance the exciting-loop current would be only 1 ampere, whereas by using a resonating condenser and the proper step-down transformer 5 amperes would flow, a clear gain of 5 in the effective ampere-turns of the primary magnetic field.

Even more essential to increased sensitivity than a large number of primary ampere-turns is the amplification of the pick-up-coil signals. First, the pick-up coil should be resonated with a condenser connected in series with it. The voltage across this condenser is then fed into a suitable amplifying unit, the output of which goes to the detector.

Typical diagrams of connections for the energizing coil and pick-up-coil systems are shown in figure 6.

Detailed descriptions and discussions of specific induction methods of prospecting appear in a later section of this report.

Objects Detectable by Induction Methods

Only metallic objects of appreciable size can be detected by induction methods. Iron chests and pots, large tin cans, and similar containers react favorably, whereas wooden or earthenware objects can produce no effects whatever, since they are neither conducting nor magnetic. It is doubtful if small quantities of coins alone could produce a measurable reaction, as they are nonmagnetic and, although conducting, do not offer large enough volumes or continuous paths for the secondary currents to produce appreciable effects. Certainly, individual scattered coins cannot be found by these methods.

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Optimum Frequency

Experience has indicated that frequencies in a range of 200 to 1,000 cycles per second are most satisfactory for induction methods of prospecting. An average value of 500 cycles per second is very convenient. Generators are obtained easily, and ordinary radio headphones can be used as a detector. Under these conditions zero voltage in the pick-up coil is evidenced by silence in the headphones, whereas secondary voltage causes an audible buzzing.

Stationary Primary Loop and Single Pick-up Coil

This method is best adapted to small areas which can be entirely surrounded by a large horizontal primary loop laid on the ground or supported a short distance above it on stakes. Actually, the loop should enclose the ground to be tested plus a strip 20 to 30 feet wide surrounding it in order to have a uniform magnetic field over the test area. (See fig. 7.) Close to the wires the magnetic lines are curved, making interpretation of anomalies in this part of the field difficult. By keeping the pick-up coil as close to the plane of energizing loop as possible still greater field uniformity is realized.

For shallow work this method should be limited to areas of less than 100 feet on a side, corresponding to an exciting loop 140 feet on a side. If a larger coil is used, even with many turns of wire, the magnetic field is too extensive and weakened too much to be effective.

The single exploring coil is mounted on a tripod in such a way that it may be rotated about both a vertical and a horizontal axis. This arrangement allows the operator to adjust the plane of the coil in any direction until it is made parallel to the magnetic field at the point of observation, as evidenced by zero voltage in the exploring coil.

The exploring coils used by the Bureau of Mines in making induction surveys of large ore bodies ranged in size from a 30-inch-diameter coil having 840 turns of No. 26 double cotton-covered wire to a 2- by 3-foot rectangular coil having 400 turns of No. 26 d. c. c. wire. The latter was more effective for nonresonant conditions, although in a search for relatively small metallic objects the circular coil with resonance should be more suitable. Figure 7,B, shows electrical connections for the pick-up-coil circuit, and figure 8 is a sketch of the mounting arrangement of the rectangular coil. Figure 9 illustrates the operating principles of this method.

Consider a section of ground devoid of any conducting bodies, as shown in figure 9,A. For such an area the primary magnetic field due to the energizing loop is represented by the series of solid lines. If a small search coil is placed in position a in such a field magnetic lines of force will pass through it, as shown, and in accordance with the laws of induction a voltage will be generated in the search coil. If the coil is now placed in position b parallel to the magnetic field the lines of force no longer pass through the coil, and no voltage is generated in it. Thus, the direction of the magnetic field at

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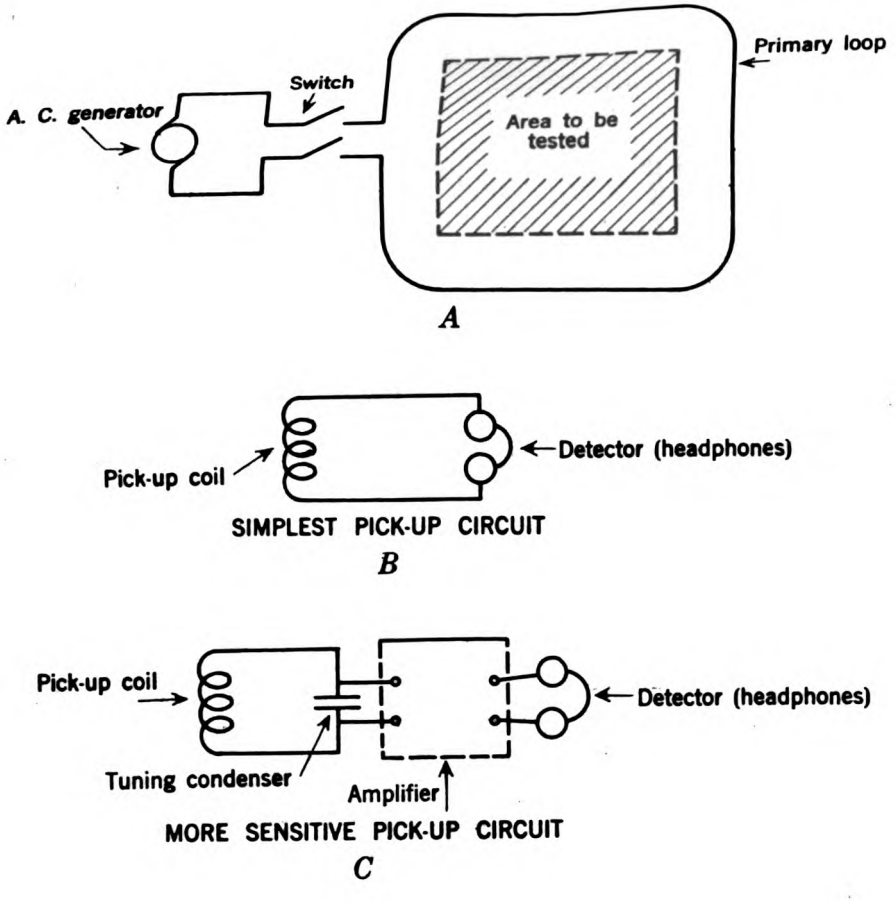

Figure 7.— *A*, Primary loop and single pick-up circuits; *B*, simplest pick-up circuit; *C*, more sensitive pick-up circuit.

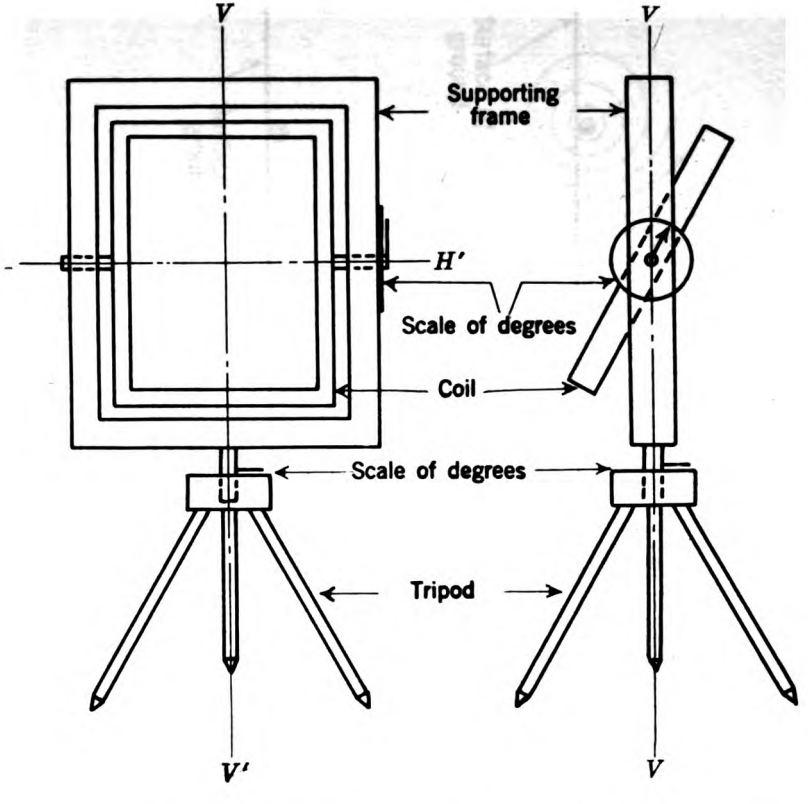

Figure 8.— Mounting arrangement of rectangular pick-up coil.

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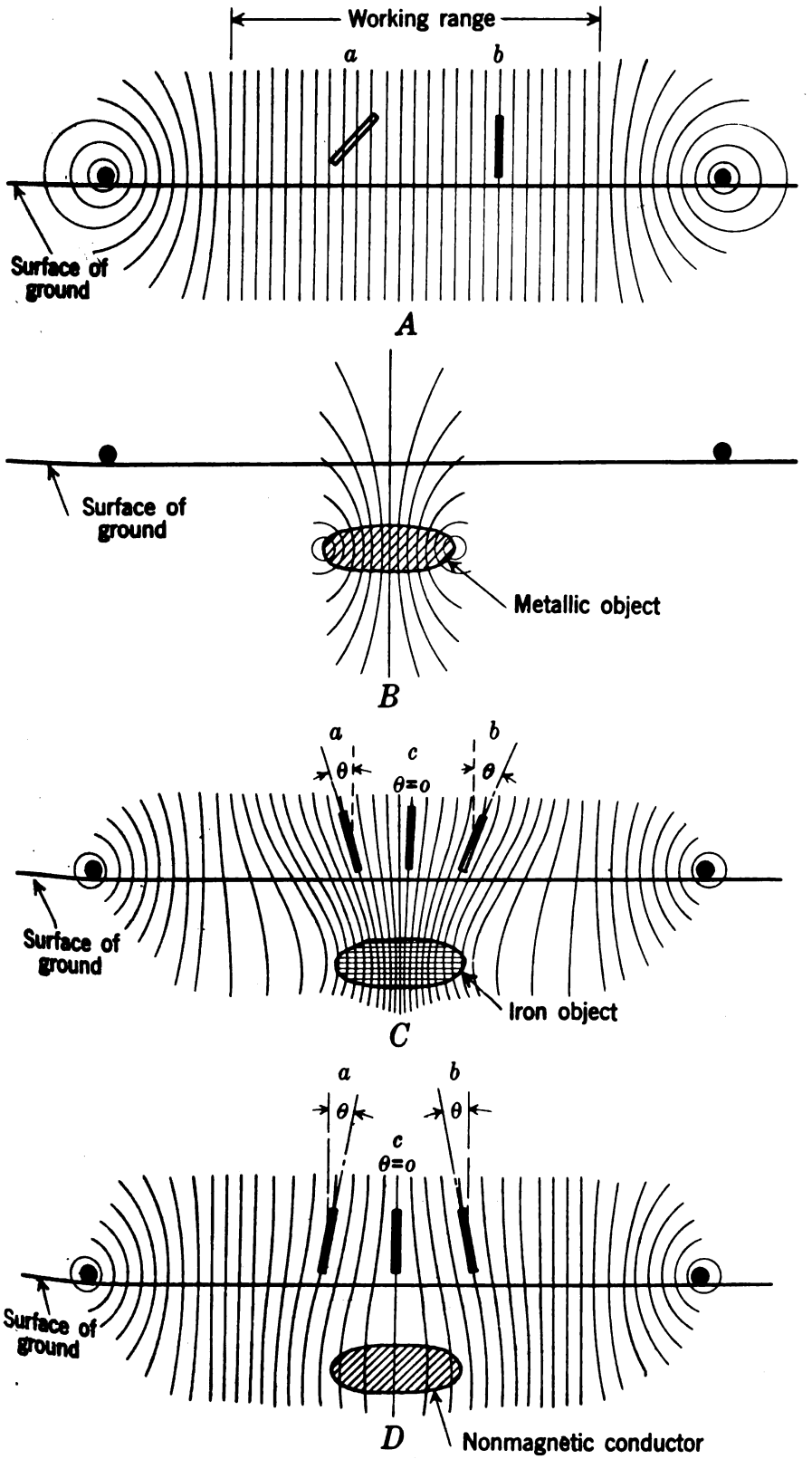

Figure 9.—Fixed exciting coil-movable pick-up coil.

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any point in the area can be determined by observing the position of the search coil at which no voltage is generated in it, as evidenced by zero response from the detecting apparatus.

By keeping the search coil within 3 feet of the ground and never closer than 20 feet from the sides of the energizing coil the operator will avoid the curved portion of the primary field, as shown in figure 9,A.

Suppose, now, that a piece of iron is placed in the field. Immediately two phenomena occur. First the magnetic lines of force of the field are crowded into the specimen because of its high magnetic permeability. Second, eddy currents are generated because the iron is an electrical conductor being cut by magnetic lines of force. These secondary currents have associated with them a magnetic field (fig. 9,B) which is opposed to the primary field, so that the crowding of lines of force due to the high permeability of the iron is to a small extent offset by this second effect. The resultant distorted field is shown greatly exaggerated in figure 9,C.

If the search coil is moved across the area shown in figure 9,C, and the positions for zero voltage are observed an anomaly or irregularity will now be found over the iron, provided, of course, that a large enough quantity is present. As the buried object is approached the search coil will indicate that the field is flexed in toward the body on either side of it (positions a and b, fig. 9,C), while directly over it (position c) the field is again more or less vertical.

For a conducting body that contains no magnetic material the secondary currents alone produce the anomaly, and the primary field is forced away from the buried object, as indicated in figure 9,D. Here, again, the search coil detects the irregularity although in this instance the field bends away from the object.

In both instances cited the probable or apparent location of the buried object is the point at which the deflection angle of the search coil (θ) changes from one side of the vertical to the other. The entire region surrounding the object must be surveyed carefully to establish this point.

It must be understood clearly that this method is applicable only where a relatively large object is to be located in a rather limited area. It is extremely doubtful whether an iron object weighing less than 100 pounds or buried deeper than 4 feet could be found, and if the object is a nonmagnetic conductor even these limits are excessive for satisfactory detection. The methods that follow are far superior for detecting smaller objects and larger areas.

The merits of this method lie in the simplicity of the apparatus and the fact that once the power loop and generator are placed they need not be moved.

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Mobile Exciting Coil-Balanced Pick-up Coils (Hughes Balanced Coils)

It is often inconvenient to use a stationary exciting coil, especially where large areas are to be investigated and the hunted object is small. Under such conditions one of the most effective methods is the so-called "Hughes balanced-coil" method.

A rigid frame is built on which are mounted an energizing coil and a system of pick-up coils. The latter are connected and placed in such positions that no secondary voltage will be generated when no metallic objects are present, but as soon as a conducting body is brought within range of the apparatus a measurable voltage is generated in the pick-up system. Such a condition may be realized in several ways.

For example, if two coils are made exactly alike in every detail each will have the same induced voltage if subjected to equal magnetic-field intensities. Now, if these two similar coils are placed at exactly equal distances on either side of an exciting coil (fig. 10) each will be cut by the same number of lines of force and consequently will have the same induced voltage. By connecting the two pick-up coils in series opposition the two induced voltages will just cancel each other, resulting in zero response in the detector.

If this coil assembly is placed over ground containing no conducting bodies the flux through each pick-up coil will remain the same (fig. 11,A), and no secondary voltage will be generated.

If, now, a magnetic conductor is present the magnetic flux from the exciting coil will be concentrated in the body, and an excess of flux will cut the lower coil, as represented by the shaded portion of the field in figure 11,B, so that its induced voltage is no longer balanced by that of the upper coil. Therefore a resultant secondary voltage will be generated, as evidenced by buzzing in the headphones. For a nonmagnetic conductor the primary field will be spread away from the object (fig. 11,C), resulting in an excess secondary voltage in the upper coil, as measured by the shaded portion of the field, and again giving rise to a resultant pick-up voltage causing a buzz in the headphones.

In theory it is necessary to carry such a device over the ground only until a signal is heard in the headphones, indicating the proximity of buried metal, which probably is located at the point where the loudest signal is heard.

In practice many difficulties and contingencies arise which must be circumvented before a reliable field outfit can be constructed. Some of these factors will now be discussed and ways of remedying them indicated.

It is essential that both pick-up coils be precisely alike in their physical dimensions and electrical properties. In winding these coils the wire must be wrapped in regular layers properly held in place so that the turns cannot shift their positions. Multilayer windings should be avoided as much as possible. In a single-layer winding capacity effects in the coils are reduced to a minimum. Where multilayer windings are used the capacities between windings become quite large and are not always equal for two coils, even though the coils have the

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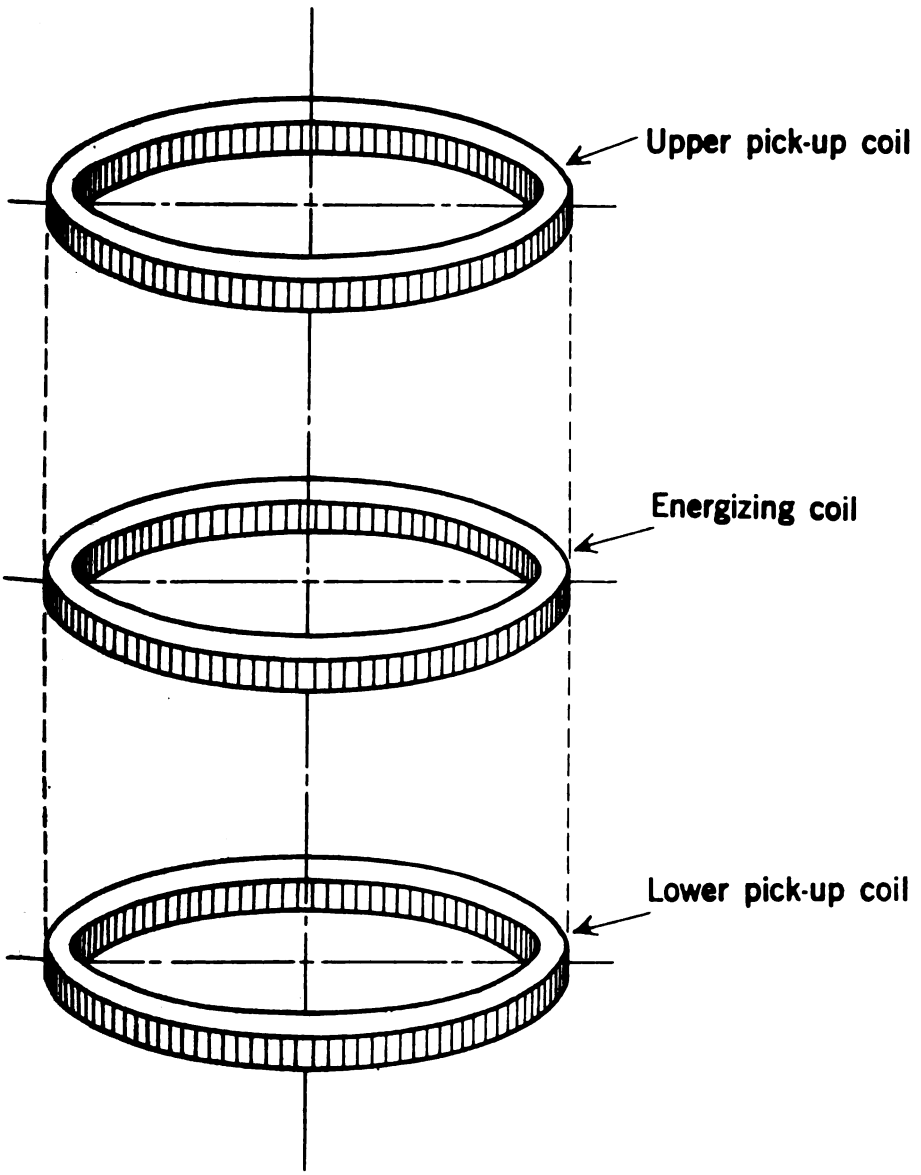

Figure 10.– Movable exciting coil and balanced pick-up-coil arrangement.

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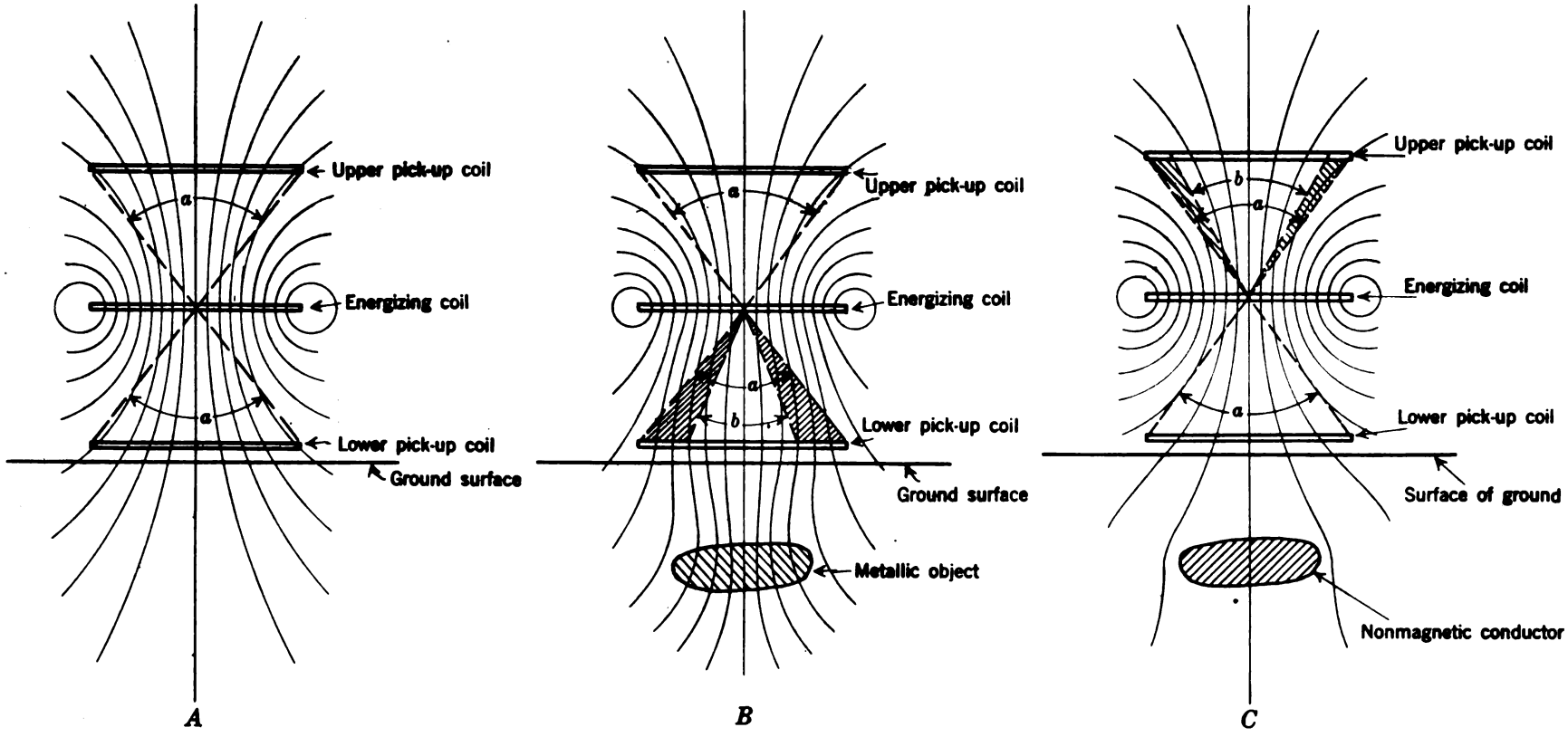

Figure 11.—Balanced pick-up-coil method.

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same number of turns and physical dimensions. In such a case it is impossible to obtain a balance between the two secondary voltages by any simple method.

The primary coil should be wound in a regular manner, and a single-layer coil should be used for the higher frequencies. Primary and secondary coils should also be far enough apart to avoid any appreciable capacity coupling from one to the other; a 6-inch separation ordinarily should suffice.

Another important point in the construction of the apparatus is to mount the coils in their proper positions so that they remain absolutely stationary relative to each other despite any ordinary shocks the apparatus may receive while in use. The carrying handles must be fastened to the coil assembly so that it will not flex while being carried, as such motion will cause the coil spacing to shift and occasion an erroneous signal in the detector.

For small coil assemblies the most satisfactory system of mounting is to wind all three coils on a single cylindrical form, suspending the latter from the carrying handles by a rope cradle. For larger outfits a rather elaborate system of internal bracing is necessary to insure rigidity.

No screws, nails, or any other bits of metal aside from the wire in the coils, should be used in the entire assembly. The coil forms and bracing should be made of well-seasoned wood held together with wooden pegs and glue. The presence of any metal results in local secondary circuits which make it difficult or even impossible to balance the two secondary pick-up-coil voltages accurately.

All coil leads must be twisted and fastened securely to the coil form to prevent them from swinging while the apparatus is being carried. Any motion of the coil leads results in disturbing induced voltages in the pick-up system. These, however, will be small for twisted leads, but for satisfactory operation they must be avoided. The generator and detector leads should be supported for a distance of 2 or 3 feet from the coil assembly by radial arms fastened to the frame. The operator wearing the headphones must be at least 20 feet from the coil assembly to prevent an audible reaction of the primary field on his headphones.

After the coil frame is assembled, a slight, final adjustment of the pick-up-coil windings usually is necessary to make the voltages in each absolutely equal. This is done by adding or subtracting turns on one of the coils until no signal is heard in the detector.

No definite limits of the sensitivity of this method can be given from a theoretical basis. Among the factors influencing sensitivity are size, shape, and composition of the buried object; character of material in which it lies; size, number of turns, and separation of the pick-up coils; size, number of turns, and current in the primary coil; degree of amplification of the pick-up-coil voltage; and sensitivity of the detector.

The larger the ratio between pick-up-coil separation and diameter and the larger the coils themselves the greater the sensitivity. Weight and awkwardness in handling impose practical limitations on the size of the apparatus used,

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since it must be portable. Coils larger than 3 feet in diameter are unwieldy, and a separation of 4 or 5 feet between pick-up coils should not be exceeded.

Figure 12 shows the electrical connections for balanced pick-up-coil methods. Figure 12,A, shows the simplest possible connection, comprising the generator, coils, and headphone detector. In figure 12,B, the sensitivity has been increased by resonating all coils and adding a secondary-voltage amplifier. As the degree of amplification is increased, more and more difficulty is encountered in obtaining an accurate secondary-voltage balance, until a point is finally reached where "background" noises in the amplifiers begin to interfere seriously with the observations. The experimenter must exercise good judgment in determining the amplification necessary for optimum results.

As an actual example of the use of this method to locate buried metallic objects, the following information taken from a report by Dr. T. Theodorsen, of the National Advisory Committee for Aeronautics,3/ is given.

A single form was used for all three coils, as shown in figure 13. The windings were wrapped in single layers, and the primary coil was supplied with 1 ampere from a small portable generator having a frequency of 500 cycles per second. The head phones used as the detector were rewound so that their impedance equaled that of the pick-up coils in series. No resonating condensers or pick-up-voltage amplifiers were used.

The entire coil assembly was held together with wooden pegs and glue, the only metal being the wire itself.

With this apparatus masses of steel weighing approximately 17 pounds were detected at depths up to 2 feet below the surface. This range proved ample for the particular problem for which the apparatus was designed and doubtless could be increased by resonating all coils and amplifying the pick-up voltage.

In conclusion, this method of induction prospecting has the advantages of portability and speed, so that relatively large areas may be covered rapidly. It is well-suited to the findings of small metallic objects relatively close to the surface. On the other hand, a skilled operator is needed if reliable results are to be obtained, and great care must be taken in the construction and adjustment of the apparatus to insure satisfactory operation.

Mobile Exciting Coil-Single Pick-up Coil

It is possible to place a single pick-up coil in such a position relative to an exciting coil that when no conducting bodies are present no voltage will be generated in the pick-up coil. On the other hand, the presence of a metallic object near the assembly will distort the magnetic field of the energizing coil and cause an induced voltage in the pick-up coil.

3/ Theodorsen, Theodore, Instrument for Detecting Metallic Bodies Buried in the Earth: Jour. Franklin Inst., vol. 210, 1930, pp. 311-326.

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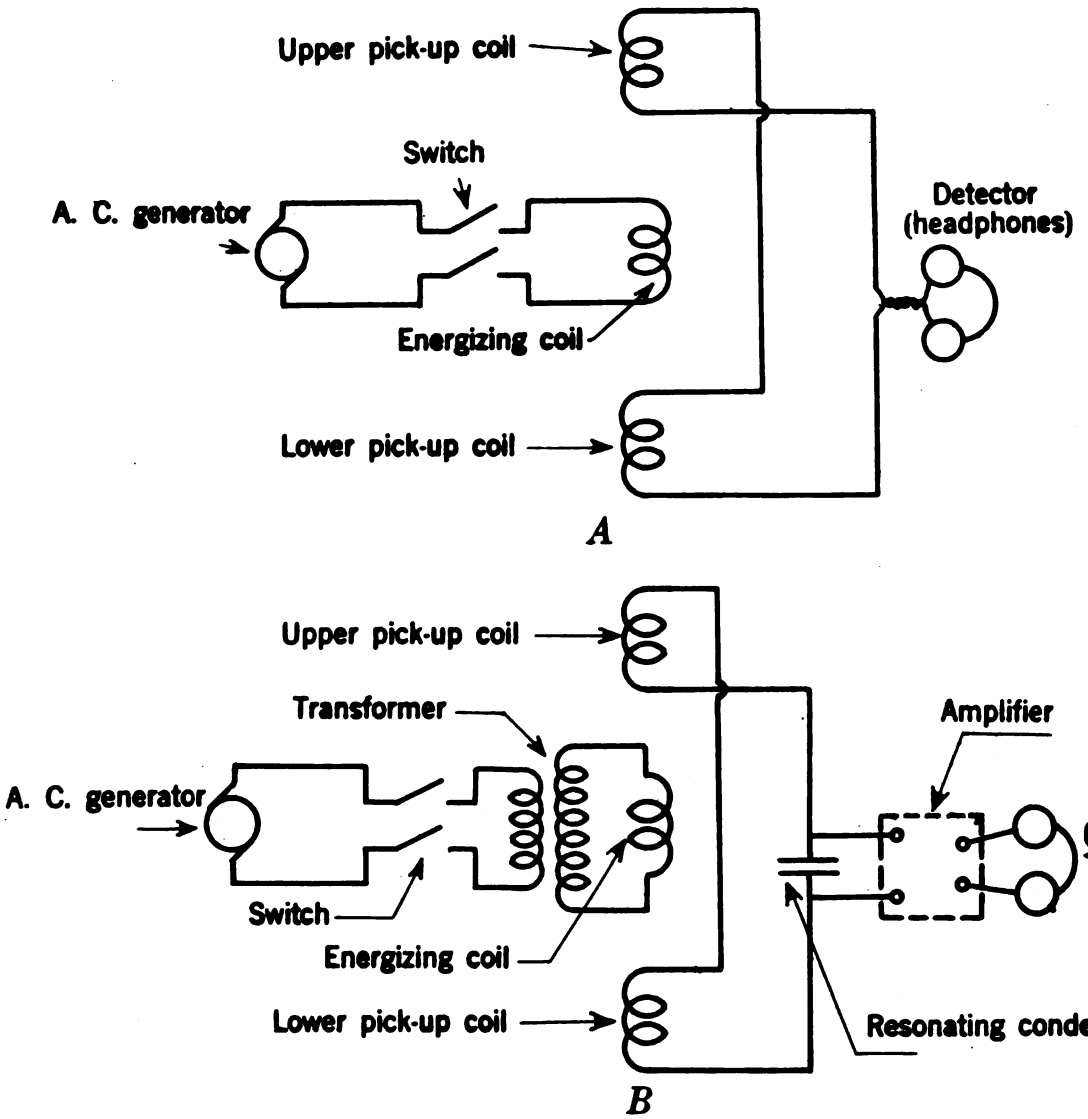

Figure 12.— Electrical connections for balanced pick-up-coil methods.

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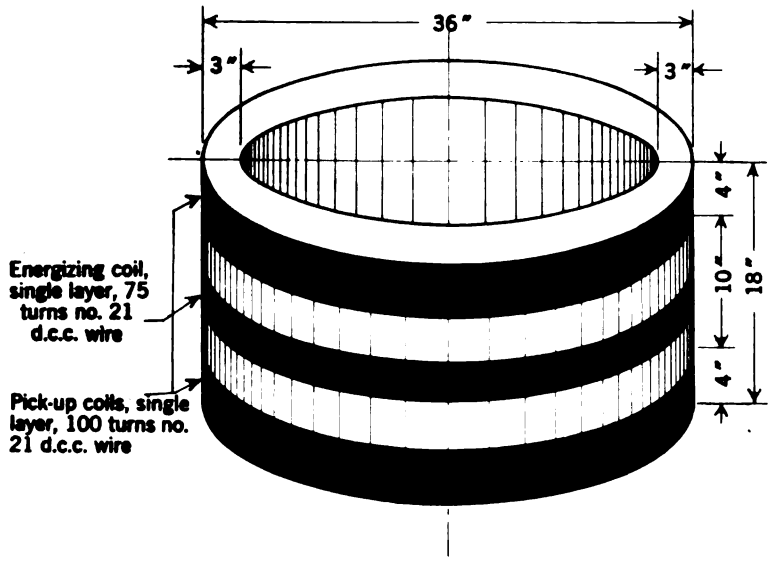

Figure 13.— Theodorsen's coil assembly.

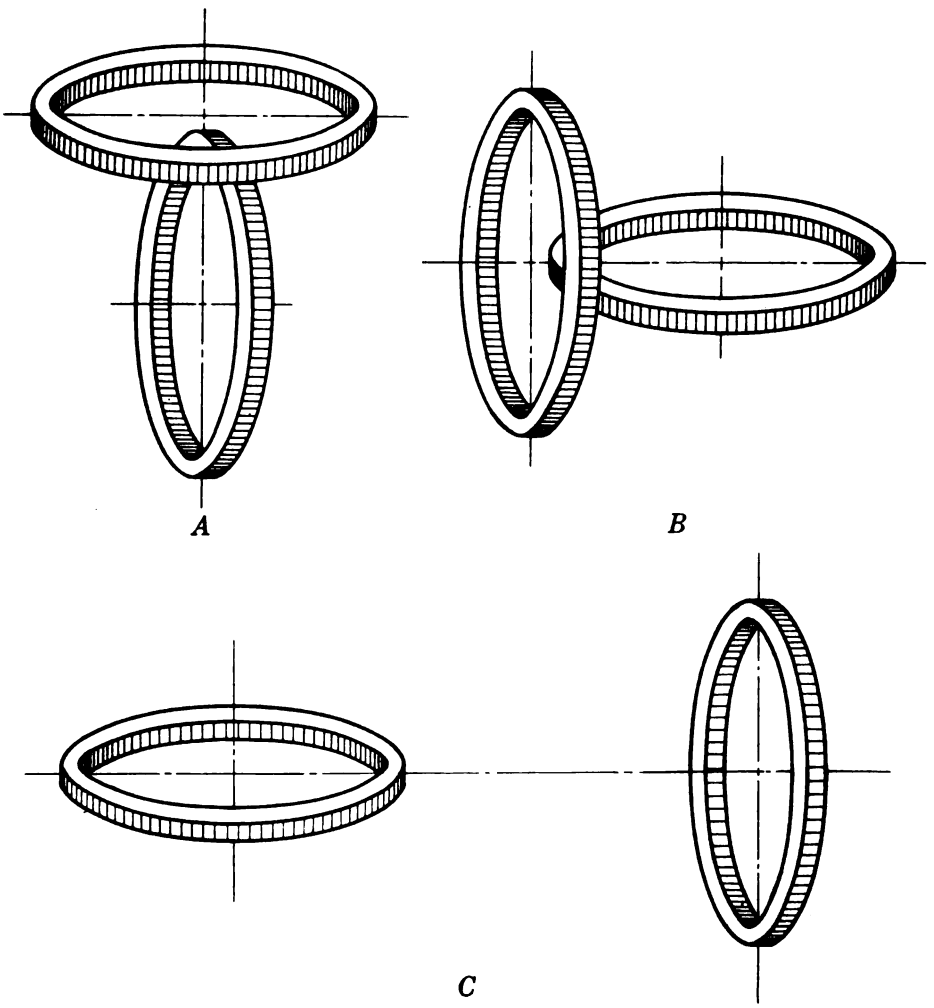

Figure 14.— Coil arrangement for movable exciting coil and single pick-up-coil method.

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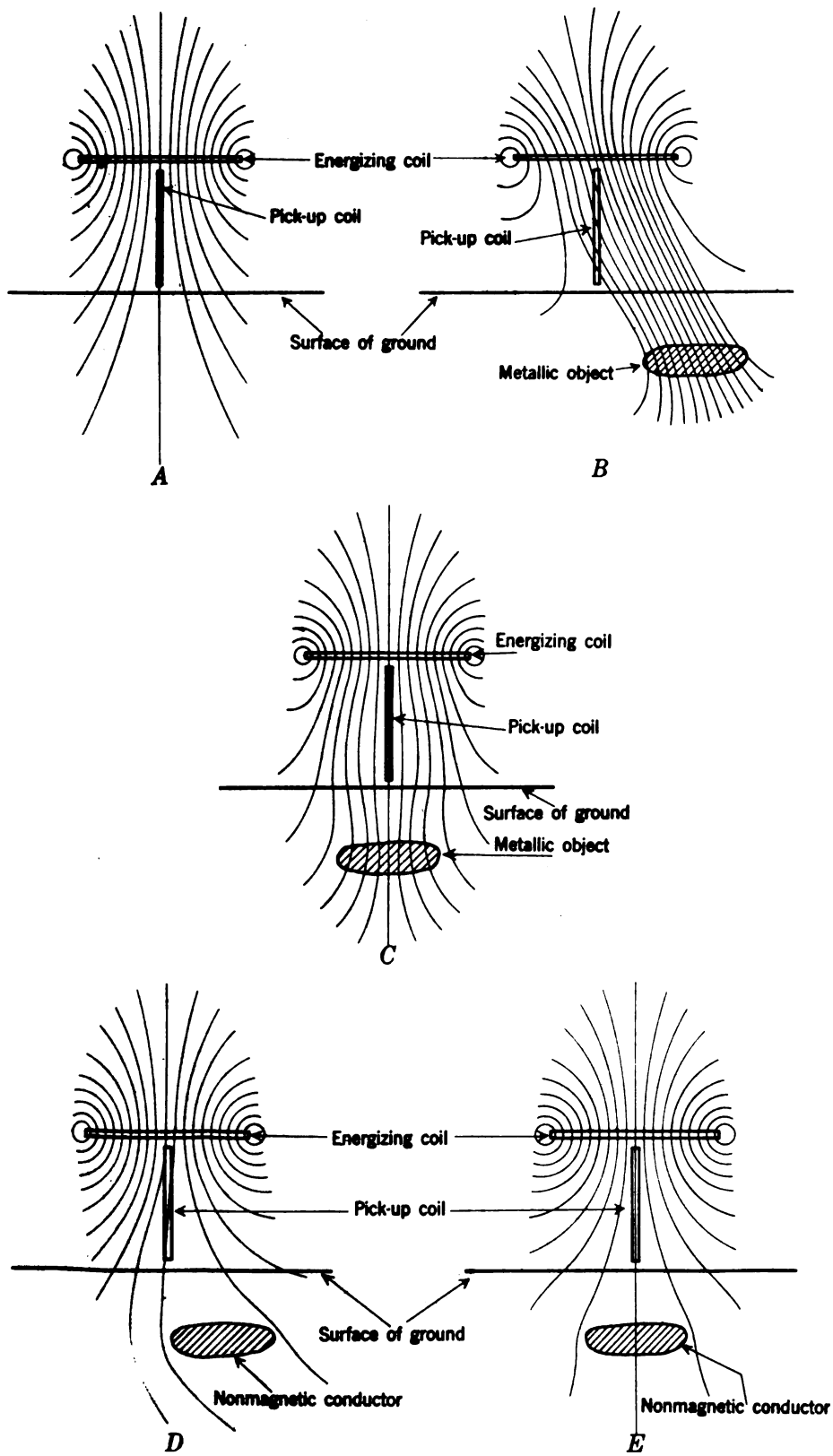

Figure 15.—Movable exciting coil and single pick-up-coil method.

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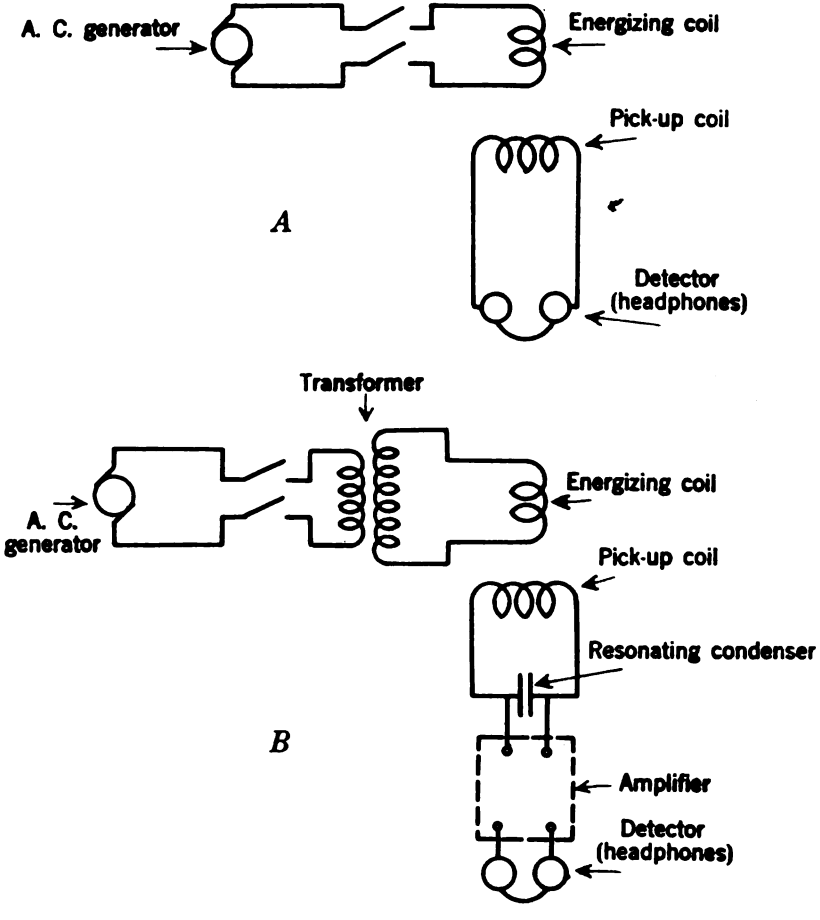

Figure 16.— Electrical connections for movable exciting coil and single pick-up-coil method.

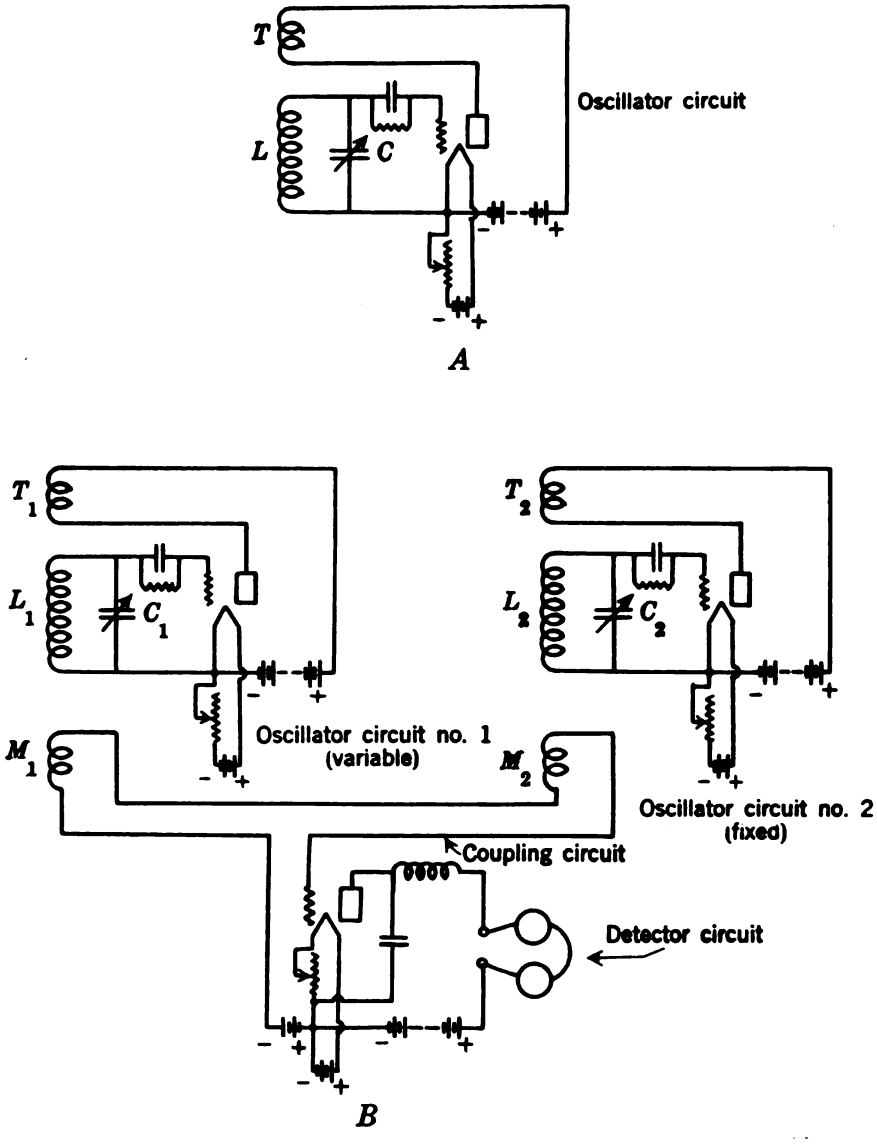

Figure 17.— Electrical circuits for beat-frequency method.

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The conditions cited above are fulfilled when the axis of one coil intersects perpendicularly that of the second coil at its center. Two examples of such an arrangement are shown in figure 14,A and B. In figure 14,C, the distance between the coils has been increased, but the same result is obtained. Moreover, either coil may be the exciting coil in such an arrangement.

For example, consider the coil arrangement given in figure 14,A, in which the exciting coil is horizontal. Then, as shown in figure 15,A, no lines of force pass through the pick-up coil, and consequently no voltage will be induced. Now, if the assembly approaches a metallic object of high magnetic permeability the field will be distorted, as shown in figure 15,B, and the magnetic lines of force will induce a voltage in the pick-up coils. If a nonmagnetic conductor is approached the field is distorted, as shown in figure 15,C, again resulting in a secondary voltage. Directly over the metallic bodies the field again parallels the plane of the pick-up coil (fig. 15,D), and no secondary voltage is generated.

By this method the presence of a buried metallic object is indicated by a signal on either side of the body, but no signal directly over it.

The electrical connections for this scheme of prospecting are shown in figure 16. The simplest arrangement is given in figure 16,A, and the most sensitive, involving resonated coils and signal amplification, in figure 16,B.

As with the balanced pick-up-coil system, numerous practical features must be considered before a successful field outfit can be built. The coils must be supported rigidly in position, and the windings should be in even layers. Single-layer coils are not essential, as with the balanced pick-up-coil method. As in the previous case, generator and pick-up-coil leads must be twisted and supported carefully, and the operator using the headphones should be 20 or more feet away from the coil assembly. No nails or other metal should be used in the coil forms and mounting frame.

In designing the coil frame it is advantageous to mount the pick-up coil so that its position relative to the energizing coil can be shifted about until, with no metallic objects present, no signal is heard. The pick-up coil should then be clamped firmly in place.

The advantages and disadvantages listed for the balanced pick-up-coil system apply equally well here. An additional favorable feature is the decrease in weight of the apparatus as a result of the elimination of one pick-up coil. The effective range probably is less than that of the balanced pick-up coils.

Beat Circuits

If a conducting body is brought near a coil carrying an alternating current the self-inductance of the coil will be reduced if the conductor is nonmagnetic and increased if it is magnetic. This simple fact is utilized in a method of prospecting which can be called the "beat-frequency" method.

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Consider the elementary oscillator shown in figure 17,A. The frequency of oscillation of this circuit is determined by the effective inductance of coil L and the capacity of condenser C. If a metallic object is now brought near L the self-inductance of the latter will be altered, and since C remains constant the frequency of oscillation will change. To observe this change to the best advantage a fixed oscillator is used as a reference frequency. It is set to a frequency equal to that of the test oscillator when no metallic body is near coil L and is shielded completely so that metallic objects nearby do not alter its frequency. Both oscillators are then coupled loosely to a detector circuit (fig. 17,B).

Coil L_1 of the test oscillator usually is wound on a large wooden form mounted on a carrying frame so that it may be moved along close to the surface of the ground. Practical details of the apparatus are included in a later section.

In operating this device search coil L_1 is held over a section of ground known to be free from metallic objects, and tuning condenser C_2 of the fixed oscillator (fig. 17,B) is adjusted until either a very low pitched note or no note at all is heard in the detector headphones. Coil L_1 is then moved over the ground, and as it approaches a metallic object the pitch of the beat note in the headphones changes. This note reaches the maximum difference of pitch at the point of nearest approach to the buried object.

In 1933 Dr. E. V. Potter, of the United States Bureau of Mines, conducted a series of preliminary investigations of this method. The actual circuits used are given in figure 18, and the details of the various coils are shown in figure 19.

It should be understood that the circuit constants given are not necessarily those recommended for prospecting. This circuit was used in the first test work, and subsequent results may justify alterations.

The first step in the design of the apparatus was the selection of the oscillator frequency, that is, the values of L_1, L_2, C_1, and C_2. This choice was governed by the facts that (1) the ground acts as a shield to the magnetic field of coil L_1 and (2) the shielding effect increases greatly with frequency - the higher the frequency the more effectively can be measured the change in inductance L_1 caused by the proximity of a metallic object, that is, the greater the range of the outfit. It was decided to investigate several frequencies in an attempt to establish experimentally the optimum value; accordingly, the circuits were arranged to cover a range of 1,000 to 2,000 kilocycles per second (1 kilocycle = 1,000 cycles). Changes were accomplished by altering the variable capacities C_1 and C_2 (fig. 18). As shown in the figure, C_2 comprises three condensers in multiple. Coarse adjustments were made with the 500- and 32-$\mu\mu$f (micromicrofarad) units and the final fine-setting with the 4-$\mu\mu$f unit.

When first assembled the two oscillators were unsteady in operation, and their frequencies shifted, causing the pitch of the note in the headphones to alter even when the apparatus was stationary. Most of this unsteadiness vanished after about an hour's operation, owing largely to a steadying of battery voltages

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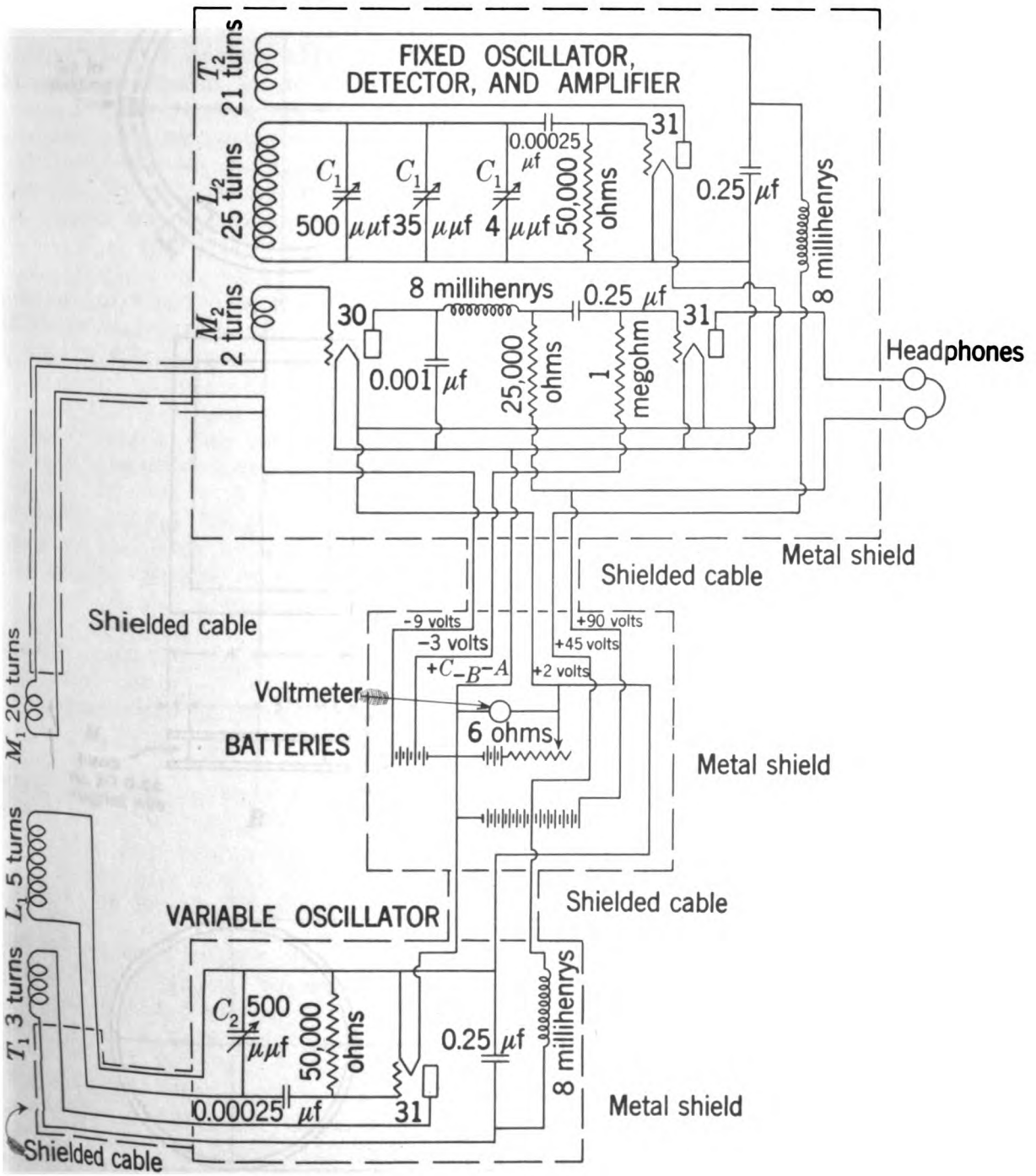

Figure 18.—Fixed oscillator, detector, and amplifier, batteries, and variable oscillator.

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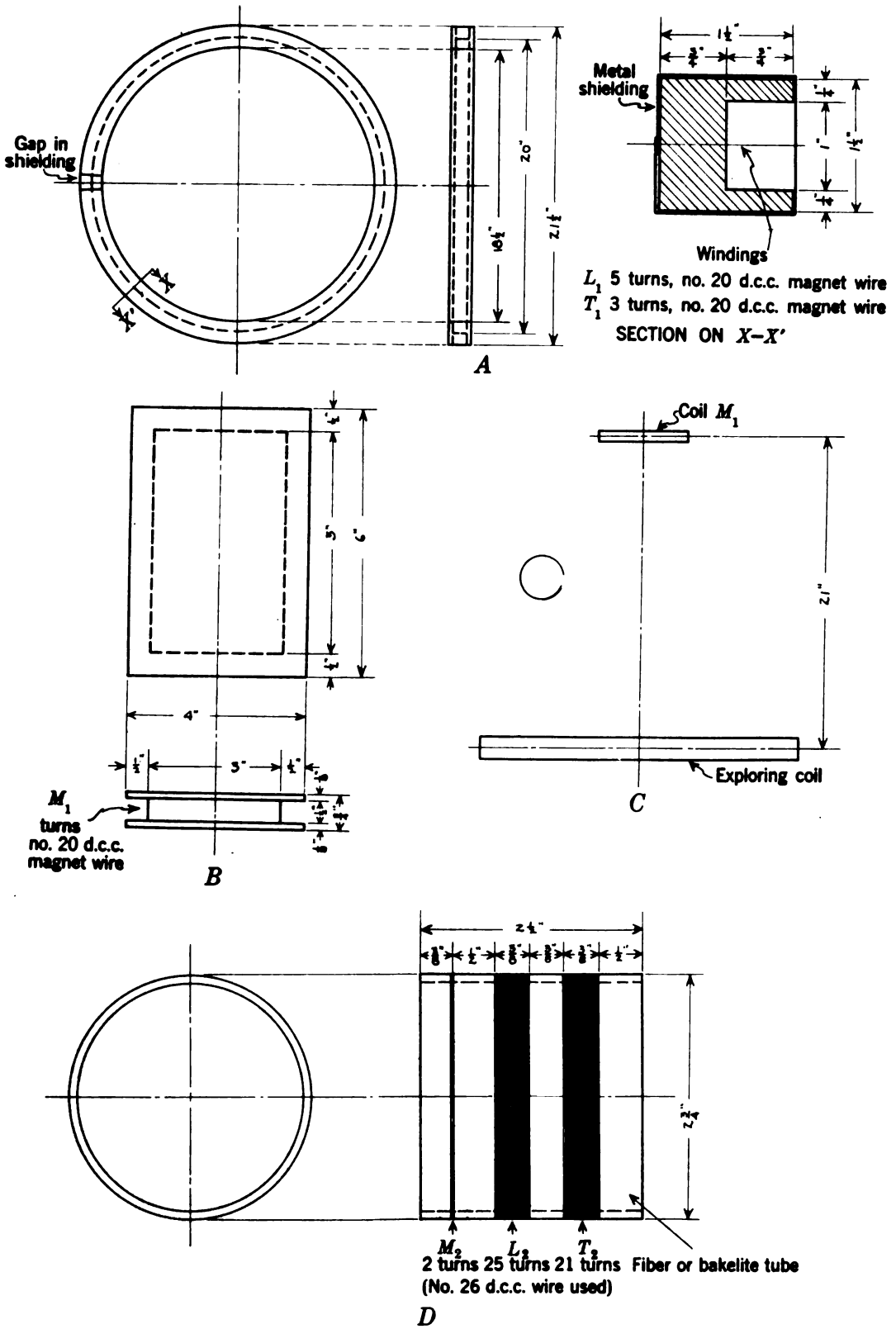

Figure 19.—*A*, Dimensions of L_1 and T_1 exploring coils; *B*, dimensions of M_1; *C*, relative positions of exploring coil (L_1 and T_1) and M_1; *D*, dimensions of M_2, L_2, and T_2.

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and the thorough heating of the vacuum tubes. Dry cells were not stable enough sources of filament current, so storage cells were substituted.

In the field tests a periodic change in the pitch of the headphone note was observed as coil L_1 was moved along the ground. This apparently is due to the change in capacity from coil to ground, which in turn is due to the varying distance between coil and the ground surface as the operators walk along with the coil. To reduce this effect the exploring coil was carefully shielded electrostatically, as shown in figure 19. The coil was enclosed in a metal wrapping except for an interval of an inch or so at one point. This gap was left to prevent the shield from forming a complete electrical circuit; in that instance secondary currents would be generated and would act as an electromagnetic shield as well. This must be avoided, as the electromagnetic effect causes the frequency of the test oscillator to change as metallic objects are approached. If shielding the coil does not remove the ground to coil-capacity effect entirely a lower oscillator frequency can be used; indeed, the results of Dr. Potter's work indicate that frequencies below 1,000 kilocycles per second probably would give better results. No opportunity for further experimental work on this question has been available.

Mounting the equipment on wheels or skids so that it can be dragged over the ground to keep the distance between coil and earth surface more or less constant should improve operations. Also, the oscillators should be carefully cushioned on sponge rubber to avoid shocks arising from the movement of the device being transmitted to the vacuum tubes or tuning condensers, as they would alter the oscillator frequency.

Variations in the detector note also were traced to slight deformations of the coil form or displacements of the battery and other connecting leads. These conditions were remedied by increasing the rigidity of the assembly and carefully fastening all wires in place.

Exception for exploring coil L_1 and detector pick-up M_1 (fig. 18), all electrical circuits and batteries were shielded in grounded metal boxes, and battery leads and other connections were carried in grounded, lead-sheath cables.

Using the equipment indicated in figures 18 and 19, an empty 5-gallon oil can could be detected 30 inches from the coil in air and about 15 inches beneath the surface of the ground, with the exploring coil 8 inches above the surface. These ranges were decreased when a smaller can was used.

An account of the construction of a "treasure" finder based on the foregoing principles is given in the July 1933 issue of Radiocraft.[4] In all probability the average builder will hardly realize the range of detection given in the article, but nevertheless, the outfit is no doubt quite sensitive.

4/ Sarver, E. Franklin, How to Build a New Treasure Finder: Radiocraft, vol. 5, July 1933, pp. 8-10.

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It must be emphasized that in constructing the oscillators only the best grade of parts should be used. Poor-quality equipment always introduces difficulties, especially in the stability of the oscillators, and stability is of primary importance in this method.

Although still more or less in the experimental stage, this method appears to have possibilities. It is rapid and has a sensitivity or range of detection as good or possibly better than any of the other schemes. Moreover, energy is supplied by batteries through the medium of oscillating circuits, making a generator unnecessary. Two men can operate it, and the cost of construction of the apparatus itself is relatively small.

The greatest disadvantage is the fact that a skillful, scientifically trained man is required to construct and operate the device. Manipulation of the circuits and the fact that weak batteries and tubes cause difficulties require a man familiar with such work for satisfactory results.

Miscellaneous Induction Problems

The various induction methods of prospecting discussed in the foregoing sections of this report are applicable to the general case of finding buried conductors. Certain specific problems, however, are handled more readily by special technic. The location of buried metal pipes falls in this category.

Consider a cross-section of ground in which a metal pipe line is buried (fig. 20). If an alternating electric current is passed along this pipe the resulting magnetic field will be concentric, as shown in the figure. If a small pick-up coil is placed in a horizontal position in such a field induced voltages will be generated for all positions of the coil except directly over the pipe (B, fig. 20). In this position the field parallels the plane of the coil, does not cut the latter, and hence generates no voltage. As a result, the detector indicates zero (that is, silence) if headphones are used.

In practice the best arrangement is to use an alternating current of 500 cycles per second frequency and to connect a pair of headphones directly across the pick-up-coil terminals or to an amplifier if one is used to obtain enough sensitivity for the particular problem at hand. With the pick-up coil held horizontally the operator walks over the ground until he reaches a point of silence. The point is then directly over the buried pipe line.

Means of electrifying the pipe will now be discussed. If both ends of the line are available a generator lead is clipped to each end, as shown in figure 21,A, and the pipe becomes an integral part of the electrical circuit. When only one end can be located a generator lead is clipped to that end, and the other is connected to an iron stake. The stake is then driven into the ground in an area over the supposed course of the pipe. The current flows along the pipe and out into the ground to the iron stake, as shown in figure 21,B. When neither end of the pipe line can be reached two stakes are connected to the generator and driven into the ground several hundred feet apart along the suspected path of the pipe (fig. 21,C). Current then flows into the ground from one stake and as the metal pipe is a good conductor tends to concentrate along the pipe, leaving it finally to enter the second stake.

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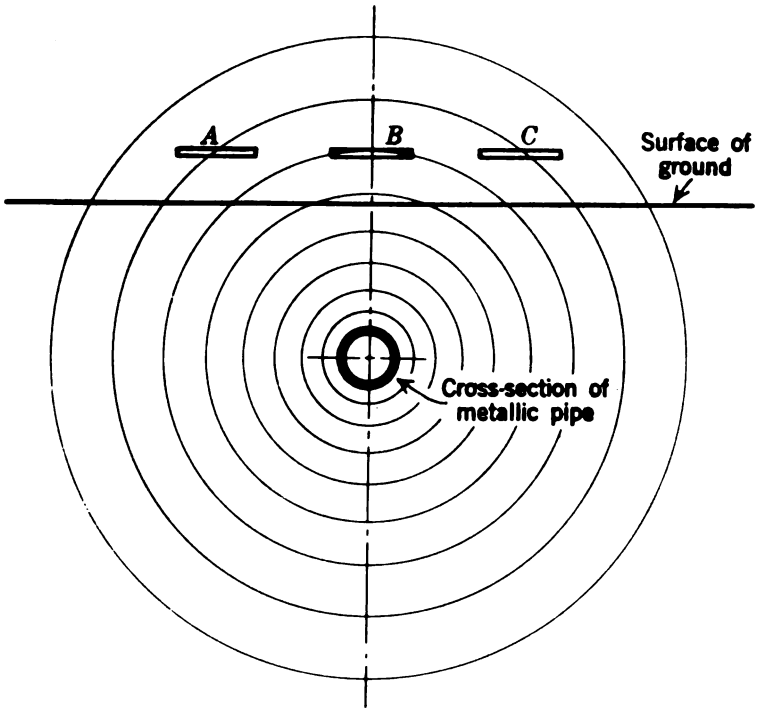

Figure 20.— Location of buried metal pipes.

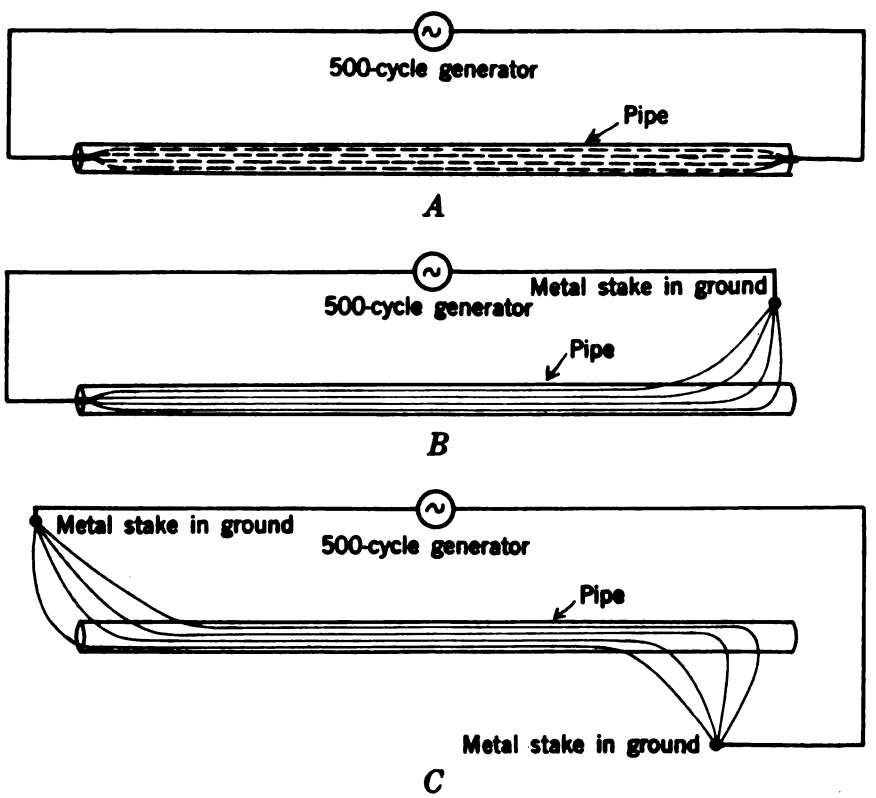

Figure 21.— Energizing buried metal pipes.

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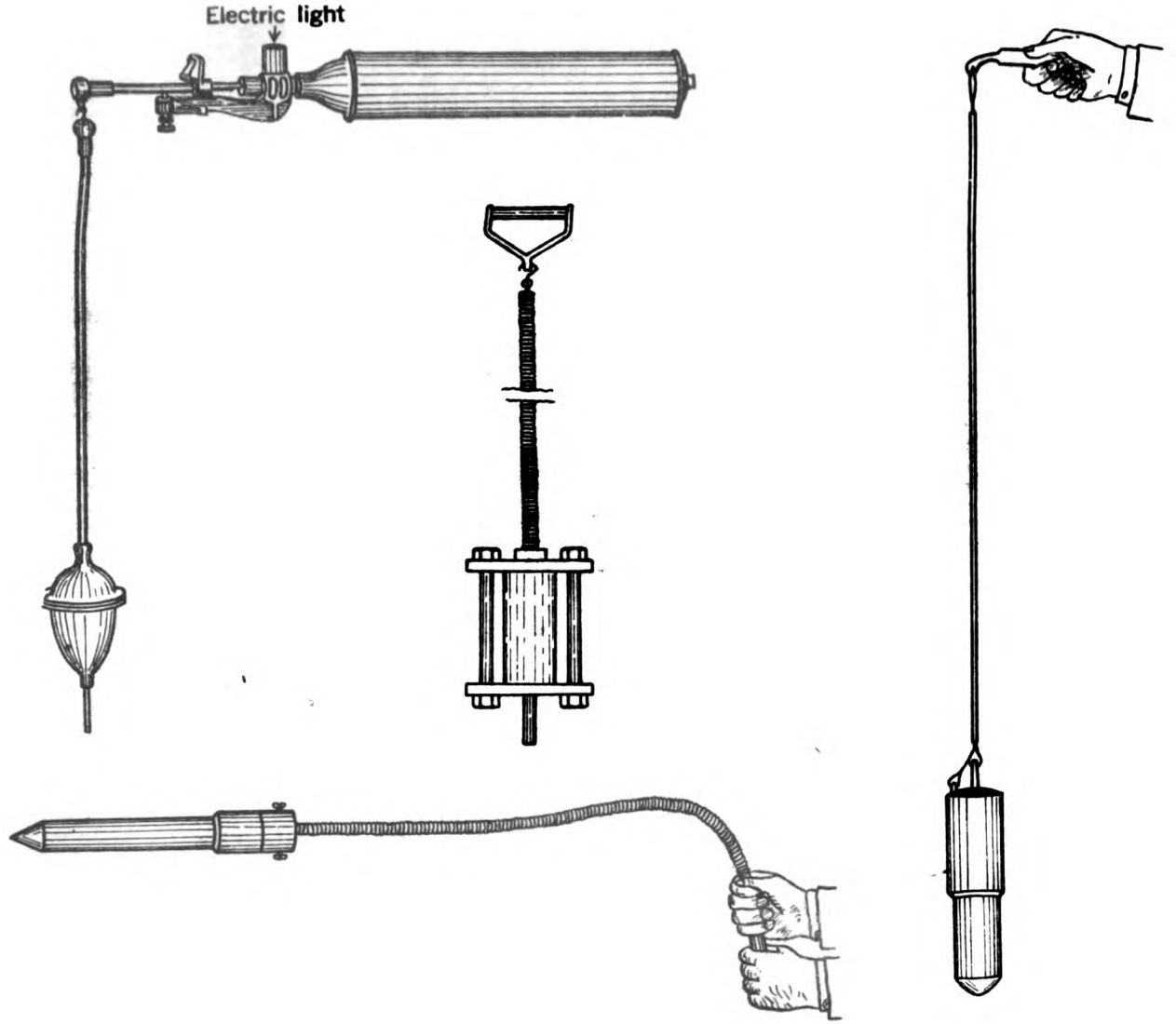

Figure 22.— Devices without scientific foundation

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As soon as the true position of the pipe line is indicated the iron stakes are moved so that they are more nearly over the pipe, the ideal location. Quite definite results thus may be realized.

Nonmetallic pipes cannot be located, as they are not electrical conductors. However, if both ends of the line can be reached and a metal wire can be worked through from one to the other and connected across the generator, the course of the pipe line may be traced.

Where short lengths of metal pipe - 15 feet or less - are to be located the general induction methods are better suited to the problem.

METHODS WITHOUT SCIENTIFIC FOUNDATION

The Divining Rod

The divining rod is the oldest of all "doodle bugs." It is mentioned in the literature for mineral exploration as early as the sixteenth century. This rod has been used in attempts to prospect minerals, treasures, water, and a host of other things.

Today the major claim made for the divining rod is that it can find water. In this capacity there are on record a few apparently well-authenticated cases of successful work, but in virtually all of these the operator was either a skilled geologist or hydrologist, and his scientific knowledge undoubtedly played an important role in his successes. In an attempt to explain its operation it has been suggested that the divining rod acts as an indicator, registering the nerve reactions of the operator, and that in some unknown manner these reactions are experienced by certain people in the vicinity of water. Such an explanation is obviously nebulous but points to the fields of physiology and psychology in addition to that of physics for its explanation, if there is any real basis for it.

No scientific ground for the operation of the divining rod is known at present, and certainly no well-informed person should risk any investment on the basis of divining-rod indications.

Fraudulent Apparatus

Self-deluded fanatics and unscrupulous individuals have offered to the public so-called treasure-finding apparatus of a wholly fradulent nature, absolutely devoid of any scientific basis. All manner of claims are made for these devices, including their ability to find oil, gas, minerals of all kinds, lost coins and treasures, buried pipes, and water.

Claims are made that operation of some of these devices is based upon "mineral vibrations". They lead one to believe that each mineral emits a unique and characteristic vibration which may be detected, disclosing the location and kind of minerals present in the ground. Scientists have not discovered any such "mineral vibrations". Radio-active elements give rise to spontaneous emanations

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of gamma rays, and the various elements when properly excited by greatly increasing their temperature emit their characteristic spectra; these phenomena, however, are entirely apart from those implied by the unscientific term "mineral vibrations".

The public is advised to carefully investigate all schemes and apparatus for which extravagant claims are made before expending any money on them.

CONCLUSION

The purpose of this paper is to describe in a general way scientifically sound methods of finding small buried metallic objects and to point out the limitations to their useful application.

It must be emphasized that at best the location of small amounts of metal is difficult, especially when nonmagnetic, as, for example, gold and silver. The location of small nonmetallic objects by the methods described is impossible.

Finally, if the best results are to be realized scientific training and experience are indispensable. Unfortunately, treasure finders have not reached the point of perfection where they can be operated indiscriminately by anyone of average ability, as is true of radios, automobiles, and similar commercial products. Treasure finders for commercial use are still in the first stages of development; as with all experimental devices, unforseen conditions and difficulties are continually arising, the solution of which requires the services of an experienced research man. The reader must realize these facts; otherwise he is doomed to disappointment in his search for hidden wealth. In general, it is wiser to employ the services of reliable individuals or companies already experienced in and equipped for such work.

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